value for which the method can be used for exploration purposes. Gravity surveying becomes increasingly appropriate as an exploration tool for those ore materials with greatest densities. The densities of a selection of metallic and non-metallic minerals and of several other materials are listed in Table 2.6.

2.3 MEASUREMENT OF GRAVITY

2.3.1 Absolute gravity

Determination of the acceleration due to gravity in absolute terms requires very careful experimental procedures and is normally only undertaken under laboratory conditions. Two methods of measurement are used, namely the falling body and swinging pendulum methods. However, it is the more easily measured *relative* variations in gravity that are of interest and value to explorationists. More detailed descriptions of how absolute gravity is measured are given by Garland (1965), Nettleton (1976) and Robinson and Coruh (1988). A popular account of gravity and its possible non-Newtonian behaviour has been given by Boslough (1989); see also Parker and Zumberge (1989).

A network of gravity stations has been established worldwide where absolute values of gravity have been determined by reference to locations where absolute gravity has been measured, such as at the National Bureau of Standards at Gaithersburg, USA, the National Physical Laboratory at Teddington, England, and Universidad Nationale de Columbia, Bogata, Columbia. The network is referred to as the *International Gravity Standardisation Net 1971* (IGSN 71) (Morelli 1971) and was established in 1963 by Woollard and Rose (1963). It is thus possible to tie in any regional gravity survey to absolute values by reference to the IGSN 71 and form a primary network of gravity stations.

2.3.2 Relative gravity

In gravity exploration it is not normally necessary to determine the absolute value of gravity, but rather it is the relative variation that is measured. A base station (which can be related to the IGSN 71) is selected and a secondary network of gravity stations is established. All gravity data acquired at stations occupied during the survey are reduced relative to the base station. If there is no need for absolute values of g to be determined, the value of gravity at a local base station is arbitrarily designated as zero. Details of the data reduction procedure are given in Section 2.5.

The spacing of gravity stations is critical to the subsequent interpretation of the data. In regional surveys, stations may be located with a density of 2–3 per km^2, whereas in exploration for hydrocarbons, the station density may be increased to 8–10 per km^2. In localised surveys where high resolution of shallow features is required, gravity stations may be spaced on a grid with sides of length 5–50 m. In micro-gravity work, the station spacing can be as small as 0.5 m.

For a gravity survey to achieve an accuracy of ± 0.1 mGal, the latitudinal position of the gravimeter must be known to within ± 10 m and the elevation to within ± 10 mm. Furthermore, in conjunction with multiple gravity readings and precision data reduction, gravity data can be obtained to within $\pm 5\,\mu$Gal (Owen 1983). The most significant causes of error in gravity surveys on land are uncertainties in station elevations. At sea, water depths are measured easily by using high-precision echo sounders. Positions are determined increasingly by satellite navigation; and in particular, the advent of the Global Positioning System (GPS) (Bullock 1988), with its compact hardware and fast response time, is resulting in GPS position-fixing becoming more precise. This is particularly true with reference to airborne gravity measurements.

2.4 GRAVITY METERS

No single instrument is capable of meeting all the requirements of every survey, so there are a variety of devices which serve different purposes. In 1749, Pierre Bouguer found that gravity could be measured using a swinging pendulum. By the nineteenth century, the pendulum was in common use to measure relative variations in gravity. The principle of operation is simple. Gravity is inversely proportional to the square of the period of oscillation (T) and directly proportional to the length of the pendulum (L) (Box 2.5). If the same pendulum is swung under identical conditions at two locations where the values of accelerations due to gravity are g_1 and g_2, then the ratio of the two values of g is the same as the ratio of the two corresponding periods of oscillation T_1 and T_2.

Box 2.5 Acceleration due to gravity from pendulum measurements

Gravity = constant × pendulum length/period² $\quad g = 4\pi^2 L/T^2$

$$\frac{(\text{Period}_1)^2}{(\text{Period}_2)^2} = \frac{\text{gravity}_2}{\text{gravity}_1} \qquad \frac{T_2^2}{T_1^2} = \frac{g_2}{g_1}$$

Further, the size of the difference in acceleration due to gravity (δg) between the two locations is (to the first order) equal to the product of gravity and twice the difference in periods $(T_2 - T_1)$ divided by the first period (Box 2.6). This method is accurate to about 1 mGal if the periods are measured over at least half an hour. Portable systems were used in exploration for hydrocarbons in the 1930s.

Box 2.6 Differences in gravitational acceleration

$$\text{Gravity difference} = -2 \times \text{gravity} \times \frac{\text{difference in periods}}{\text{period}_1};$$

$$\delta g = -2g\,\frac{(T_2 - T_1)}{T_1}$$

Another method of determining relative gravity is that of the torsion balance (Figure 2.6). English physicist Henry Cavendish devised this system to measure the gravitational constant in 1791. The method was developed for geodetic purposes in 1880 by a Hungarian physicist, Baron Roland von Eötvös. After further modification it was used in exploration from 1915 to the late 1940s. The method, which measures variations in only the horizontal component of gravity due to terrain and not vertical gravity, is capable of very great sensitivity (to 0.001 mGal) but is awkward and very slow to use in the field. The method is described in more detail by Telford *et al.* (1990).

Since about the early 1930s, variations in relative gravity have been measured using gravity meters (gravimeters), firstly stable (static) and

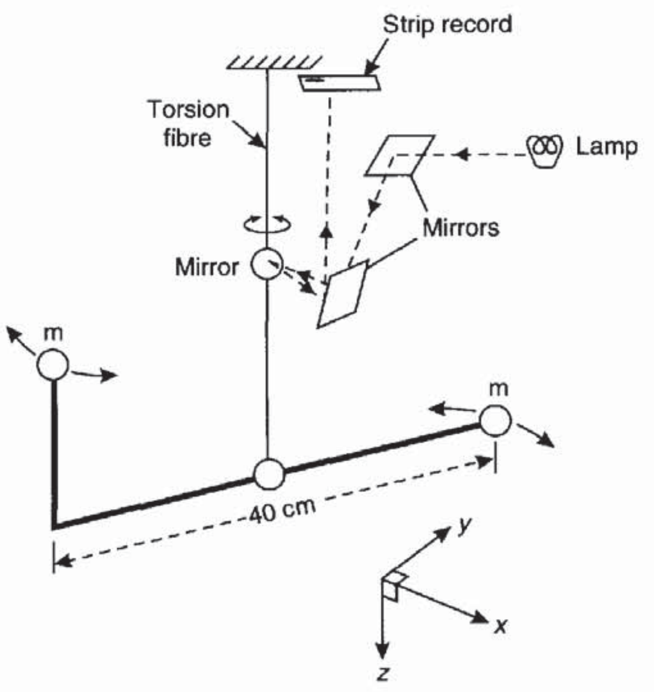

Figure 2.6 Schematic of a torsion balance

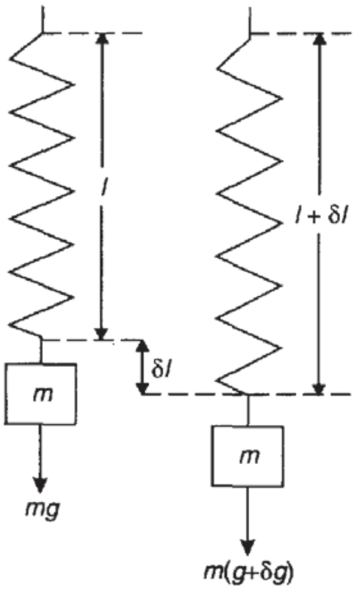

Figure 2.7 Extension (δl) of a spring due to additional gravitational pull (δg)

more recently unstable (astatic) types. Practical aspects of how to use such instruments have been detailed by Milsom (1989, Ch. 2). Gravimeters are sophisticated spring balances from which a constant mass is suspended (Figure 2.7). The weight of the mass is the product of the mass and the acceleration due to gravity. The greater the weight acting on the spring, the more the spring is stretched. The amount of extension (δl) of the spring is proportional to the extending force, i.e. the excess weight of the mass (δg). (Remember that weight equals mass times acceleration due to gravity.) The constant of proportionality is the elastic spring constant κ. This relationship is known as Hooke's Law (Box 2.7).

As the mass is constant, variations in weight are caused by changes in gravity (δg). By measuring the extension of the spring (δl), differences in gravity can then be determined. As the variations in g are very small (1 part in 10^8) the extension of any spring will also be extremely tiny. For a spring 30 cm long, changes in length of the order of 3×10^{-8} m (30 nanometres) have to be measured. Such small distances are even smaller than the wavelength of light (380–780 nm). Consequently, gravimeters use some form of system to amplify the movement so that it can be measured accurately.

Box 2.7 Hooke's Law

Extension to spring = mass × $\frac{\text{change in gravity}}{\text{spring constant}}$	$\delta l = \frac{m\delta g}{\kappa}$
Change in gravity = constant × extension/mass	$\delta g = \kappa \delta l / m$

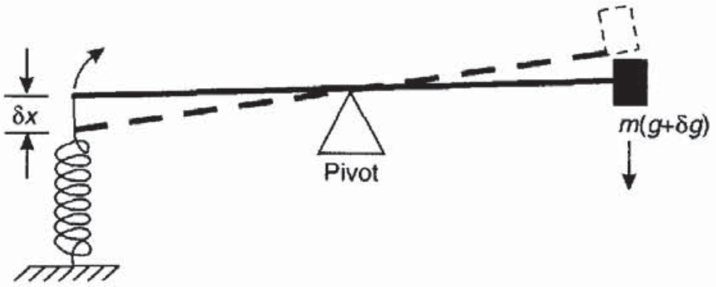

Figure 2.8 Basic principle of operation of a stable gravimeter

2.4.1 Stable (static) gravimeters

Stable gravimeters (Figure 2.8), which were developed in the 1930s, are less sensitive than their more modern cousins, the unstable gravimeters, which have largely superseded them. The stable gravimeter consists of a mass at the end of a beam which is pivoted on a fulcrum and balanced by a tensioned spring at the other end. Changes in gravity affect the weight of the mass which is counterbalanced by the restoring action of the spring. Different configurations of stable gravimeters are shown in Figure 2.9 and are discussed in more detail by Garland (1965), Nettleton (1976), Telford *et al.* (1990), and Parasnis (1986). A brief description of three stable gravimeters is given below.

2.4.1.1 Askania

A beam with a mass at one end is pivoted on a main spring S (Figure 2.9A). Changes in gravity cause the beam to tilt, so producing a deflection in a beam of light which is reflected off a mirror placed on the mass. A photoelectric cell, the output of which is displayed on a galvanometer, measures the displacement of the light beam. An auxiliary spring (AS) is retensioned using a micrometer to restore the mass to its rest position, which is indicted when the galvanometer reading is returned to zero (nulled).

2.4.1.2 Boliden

The Boliden gravimeter uses the principle that the capacitance of a parallel-plate capacitor changes with the separation of the plates (Figure 2.9B). The mass has the form of a bobbin with a plate at each end and is suspended by two springs between two other capacitor plates. With a change in gravity, the mass moves relative to the fixed plates, changing the capacitance between the upper plates; this movement can be detected easily using a tuned circuit. The lower plates are connected to a d.c. supply which supports the bobbin mass by electrostatic repulsion. With a change in gravity and the consequent displacement of the bobbin relative to the fixed plates, the original or

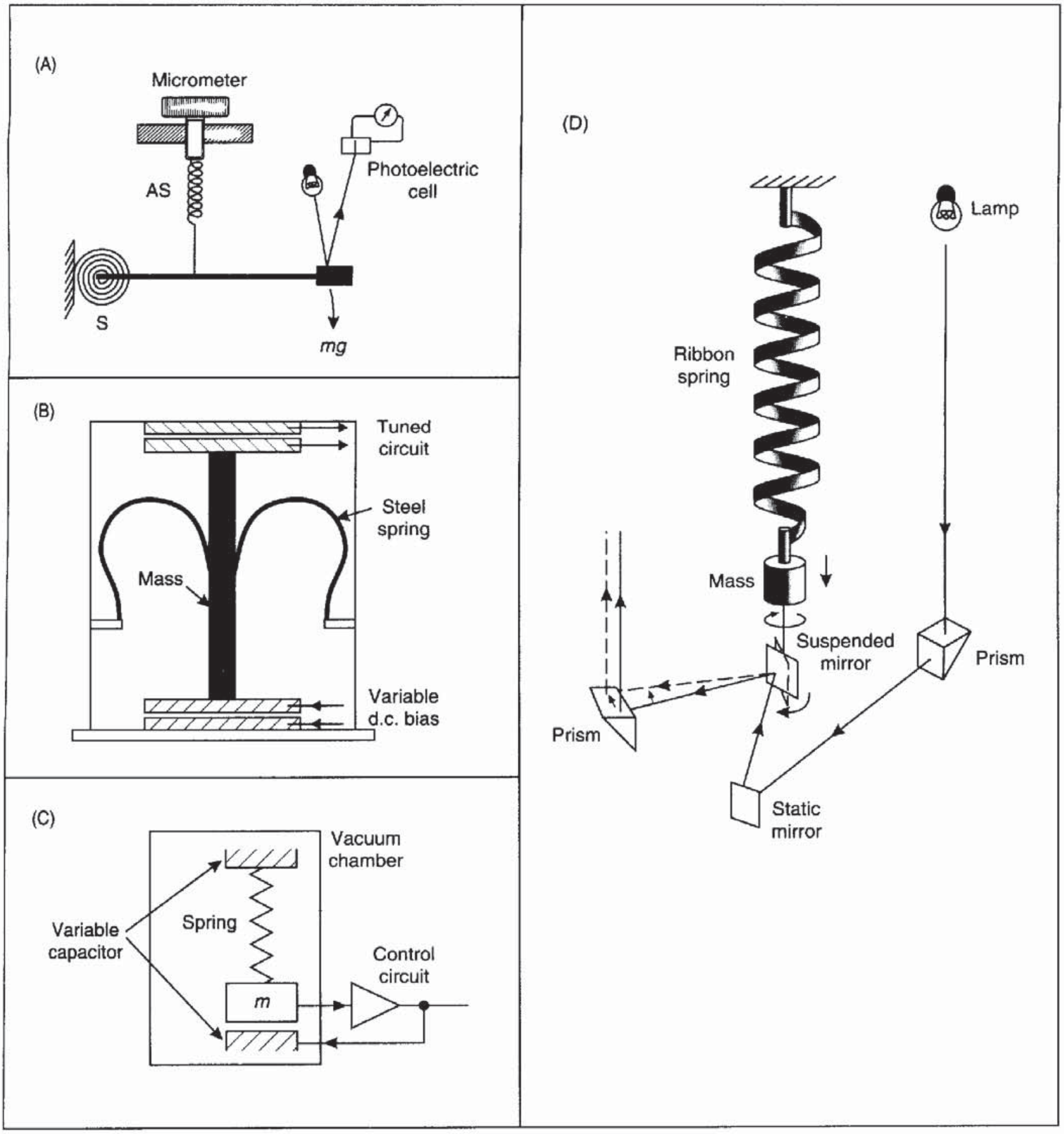

Figure 2.9 Types of stable gravimeter: (A) Askania; (B) Boliden; (C) Scintrex CG-3; and (D) Gulf (Hoyt). After Garland (1965), Telford *et al.* (1976), Robinson and Coruh (1988), by permission

a reference position can be obtained by changing the direct voltage between the lower pair of plates. The overall sensitivity is about 1 g.u. (0.1 mGal). A modern version has been produced by Scintrex (Model CG-3) which operates on a similar principle (see Figure 2.9C). Any displacement of the mass due to a change in gravity is detected by a capacitor transducer and activates a feedback circuit. The mass is returned to its null position by the application of a direct feedback voltage (which is proportional to the change in gravity) to the plates of the capacitor which changes the electrostatic force between the plates and the mass (Robinson and Coruh 1988).

2.4.1.3 Gulf (Hoyt)

The Gulf gravimeter comprises a coiled helical ribbon spring which rotates as it changes length (Figure 2.9D). The rotation of the free end of the spring is much larger than the change in length and so is more easily measured. The range of measurement is quite small, being only 300 g.u. (30 mGal), although this can be overcome to some extent by retensioning the spring, and the accuracy of measurement is to within 0.2–0.5 g.u. (0.02–0.05 mGal).

2.4.2 Unstable (astatic) gravimeters

Since the 1930s, unstable gravimeters have been used far more extensively than their stable counterparts. In a stable device, once the system has been disturbed it will return to its original position, whereas an unstable device will move further away from its original position.

For example, if a pencil lying flat on a table is lifted at one end and then allowed to drop, the pencil will return to being flat on the table. However, if the pencil starts by being balanced on its end, once disturbed, it will fall over; i.e. it becomes unstable, rather than returning to its rest position. The main point of the instability is to exaggerate any movement, so making it easier to measure, and it is this principle on which the unstable gravimeter is based.

Various models of gravimeter use different devices to achieve the instability. The principle of an astatic gravimeter is shown in Figure 2.10. An almost horizontal beam hinged at one end supports a mass at the other. The beam is attached to a main spring which is connected at its upper end to a support above the hinge. The spring attempts to pull the beam up anticlockwise by its turning moment, which is equal to the restoring force in the spring multiplied by the perpendicular distance from the hinge (d). This turning moment is balanced by the gravitational turning moment which attempts to rotate the beam in a clockwise manner about the hinge and is equal to the weight of the mass (mg) times the length of the beam (l) multiplied by the cosine of the angle of the beam from the horizontal (θ) (i.e. $mgl\cos\theta$). If gravity changes, the beam will move in response but will be maintained in its new position because the main spring is a 'zero-length' spring. One virtue of such a spring is that it is pretensioned during manufacture so that the tension in the spring is proportional to its length. This means that if all forces were removed from the

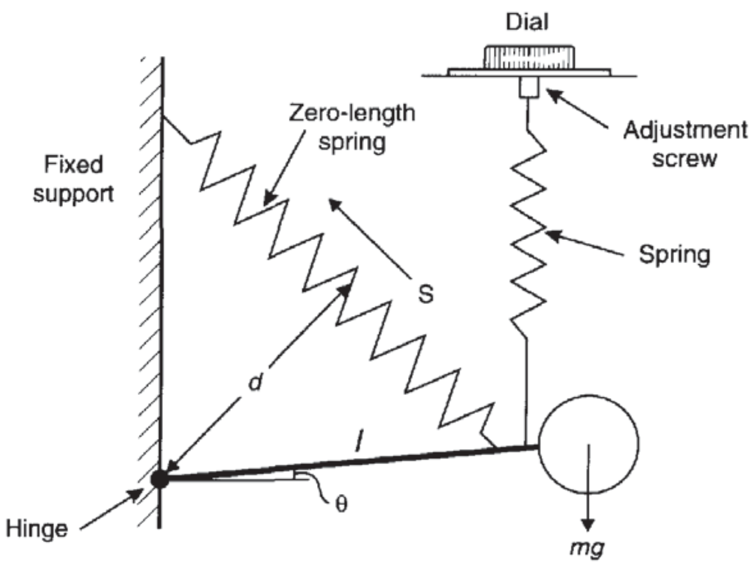

Figure 2.10 Principle of operation of an astatic gravimeter

spring it would collapse to zero length, something which is impossible in practice. Another virtue of the zero-length spring is that it results in an instrument which is linear and very responsive over a wide range of gravity values. Astatic gravimeters do not measure the movement of the mass in terms of changes in gravity but require the displaced mass to be restored to a null position by the use of a micrometer. The micrometer reading is multiplied by an instrumental calibration factor to give values of gravity, normally to an accuracy within 0.1 g.u. (0.01 mGal) and in some specialist devices to within 0.01 g.u. (0.001 mGal = 1 μGal).

2.4.2.1 Thyssen

Although obsolete, this gravimeter demonstrates the instability concept extremely well and is included for this reason. An extra mass is placed above a balanced beam (Figure 2.11) so producing the instability condition. If gravity increases, the beam tilts to the right and the

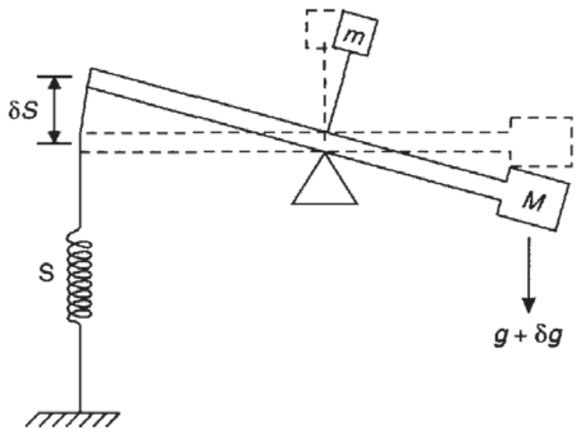

Figure 2.11 Schematic of a Thyssen gravimeter

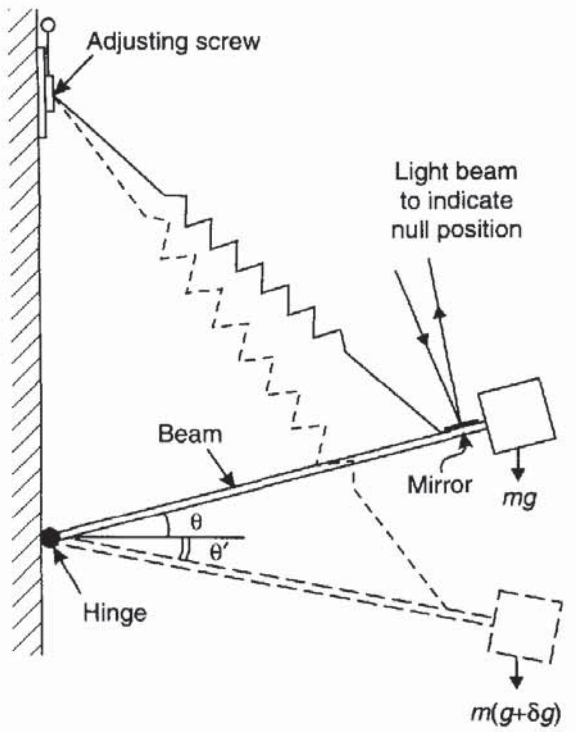

Figure 2.12 Schematic of a LaCoste-Romberg gravimeter. After Kearey and Brooks (1991), by permission

movement of the extra mass enhances the clockwise rotation about the pivot, and conversely for a reduction in gravity. When used, this type of gravimeter had a sensitivity of about 2.5 g.u. (0.25 mGal).

2.4.2.2 LaCoste–Romberg

This device is a development of LaCoste's long-period seismograph (LaCoste 1934) and is illustrated in Figure 2.12. The spring is made of metal with a high thermal conductivity but cannot be insulated totally to eradicate thermal effects and so has to be housed permanently in an enclosed container in which a stable temperature is maintained to within 0.002°C by a thermostat element. The null point is obtained by the observer viewing a scale through an eyepiece onto which a beam of light is reflected from the beam when it is in its rest position. In order to restore the position of the beam, the operator rotates a micrometer gauge on the outer casing which turns a screw which adjusts the beam position. The long length of the screw means that the gravimeter can be used worldwide without having to undergo any resets, which is a major advantage over other makes for surveys where this is important. When this type of gravimeter was manufactured in the 1930s it weighed a massive 30 kg, but modern technology has made it possible for the weight to be reduced to only about 2 kg, excluding the battery required to maintain the heating coils. The springs can be clamped and so the gravimeter is more easily transportable than other makes and also less sensitive to vibration. It is possible for some models of LaCoste–Romberg gravimeters to measure to 3 μGal.

2.4.2.3 Worden

Unlike the LaCoste–Romberg gravimeter, the Worden is made entirely of quartz glass springs, rods and fibres (Figure 2.13). The quartz construction makes it much easier to reduce thermal effects. Indeed, the whole assembly is housed in a glass vacuum flask and some models have an electrical thermostat. As the spring cannot be clamped, the Worden gravimeter is sensitive to vibration and has to be transported extremely carefully. The range of the instrument is about 20 000 g.u. (2000 mGal) with an accuracy to within 0.1–0.2 g.u. (0.01–0.02 mGal). However, quartz gravimeters such as the Worden can be quite difficult for inexperienced operators to read and a realistic accuracy may be more like 1 g.u. (0.1 mGal). The Worden gravimeter has two auxiliary springs, one for coarse and the other for fine adjustments.

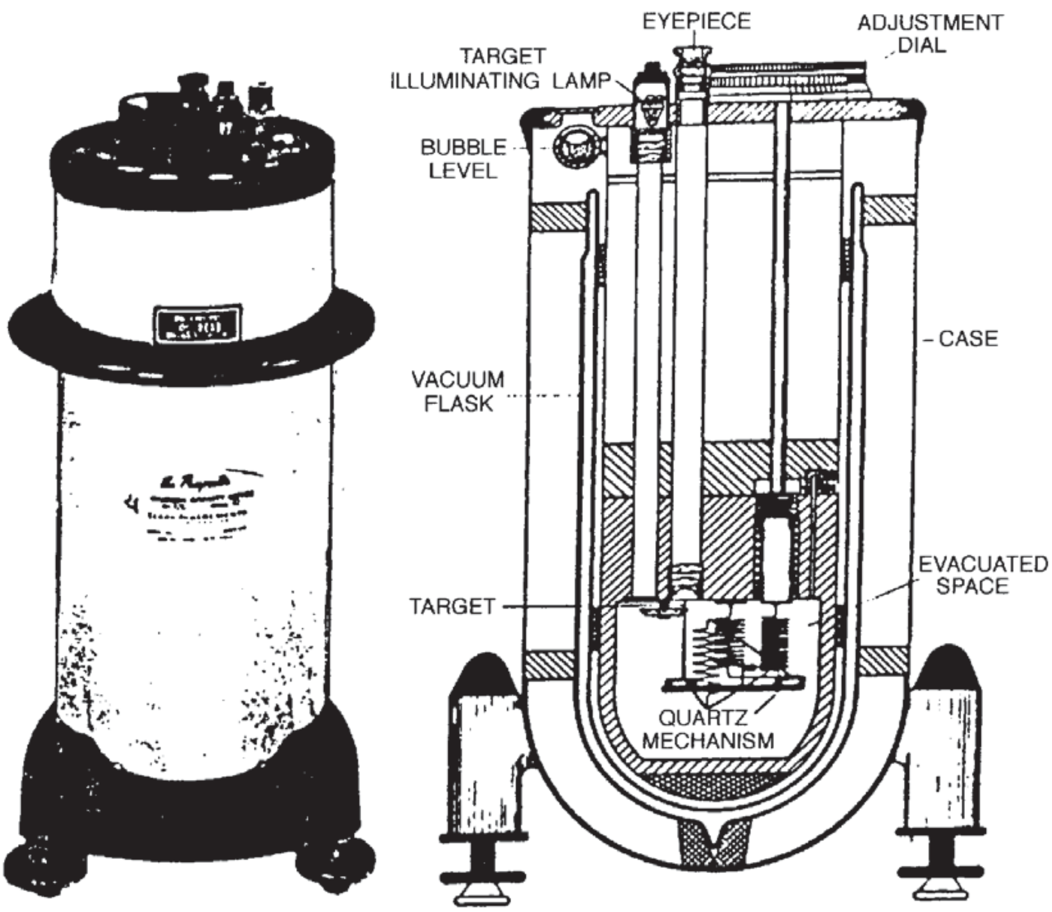

Figure 2.13 Cross-section through a Worden gravimeter (Texas Instruments Ltd). From Dunning (1970), by permission

2.4.2.4 *Sodin*

This is very comparable to the Worden and operates in similar ways. Further details are given by Robinson and Coruh (1988).

2.4.2.5 *Vibrating string*

If a mass is suspended on a fibre which is forced to oscillate by an a.c. circuit, then the frequency of vibration, which can be measured electronically, will vary with changes in gravity. For a fibre of length L, and mass per unit length m_s, from which a mass M is suspended, by measuring the frequency of vibration (f), gravity can be determined (Box 2.8). However, the technology is not sufficiently developed to provide the same resolution and accuracy as other gravimeters, but it does give the impression that even more compact and lightweight gravimeters may be forthcoming in the near future. There is potential for use in airborne survey systems.

Box 2.8 Determination of *g* using a vibrating string

$$\text{Gravity} = \frac{4 \times \text{string length}^2 \times \text{frequency}^2 \times \text{string mass}}{\text{suspended mass}};$$

$$g = \frac{4L^2 f^2 m_s}{M}$$

2.5 CORRECTIONS TO GRAVITY OBSERVATIONS

Gravimeters do not give direct measurements of gravity. Rather, a meter reading is taken which is then multiplied by an instrumental calibration factor to produce a value of observed gravity (g_{obs}). Before the results of the survey can be interpreted in geological terms, these raw gravity data have to be corrected to a common datum, such as sea level (geoid), in order to remove the effects of features that are only of indirect geological interest. The correction process is known as *gravity data reduction* or *reduction to the geoid*. The difference between the value of observed gravity (g_{obs}) and that determined either from the International Gravity Formula/Geodetic Reference System 67 for the same location, or relative to a local base station, is known as the *gravity anomaly*. The various corrections that can be applied are listed in Table 2.7 with the sections of this book in which each one is discussed.